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ECHELLE SPECTROSCOPY OF A GAMMA-RAY BURST AFTERGLOW AT $z = 3.969$: A NEW PROBE OF THE INTERSTELLAR AND INTERGALACTIC MEDIA IN THE YOUNG UNIVERSE

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ABSTRACT

We present an echelle spectrum of the *Swift* GRB 050730, obtained 4 hr after the burst using the MIKE spectrograph on the Magellan Clay telescope when the afterglow was at $R = 17.7$. The spectrum reveals a forest of absorption features superposed on a simple power-law shaped continuum, best described as $f_\nu(\lambda) \propto \lambda^\alpha$ with $\alpha = 1.88 \pm 0.01$ over $\lambda = 7000$–9000 Å. We identify the gamma-ray burst (GRB) host at $z_{\rm GRB} = 3.96855$ based on the hydrogen Lyman absorption series, narrow absorption lines due to heavy ions such as O I, C II, Si II, S II, Ni II, Fe II, C IV, Si IV, and N V, and fine-structure transitions such as O I*, O I**, Si II*, C II*, and Fe II*. Together these transitions allow us to study the properties of the interstellar medium (ISM) in the GRB host. The principal results are as follows. (1) We estimate a neutral hydrogen column density of log N(H I) $= 22.15 \pm 0.05$ in the host. (2) The associated metal lines exhibit multiple components over a velocity range of ~80 km s^{-1}, with >90% of the neutral gas confined in 20 km s^{-1}. (3) Comparisons between different ionic transitions show that the host has little or no dust depletion and has 1/100 solar metallicity. (4) The absorbing gas has much higher density than that of intervening damped Lyα absorption (DLA) systems. In addition, we report the identification of an intervening DLA system at $z_{\rm DLA} = 3.56439$ with log N(H I) $= 20.3 \pm 0.1$ and <5% solar metallicity, a Lyman limit system at $z_{\rm LLS} = 3.02209$ with log N(H I) $= 19.9 \pm 0.1$, a strong Mg II absorber at $z_{\rm Mg\,II} = 2.25313$, and a pair of Mg II absorbers at $z_{\rm Mg\,II} = 1.7731$, 57 km s^{-1} apart. We demonstrate that rapid echelle spectroscopy of GRB afterglows helps to reveal a wealth of information in the ISM and the intergalactic medium along the sight line, which, when followed up with late-time deep imaging, will allow us to uncover a sample of distant galaxies with known ISM properties to constrain galaxy formation models.

Subject headings: gamma rays: bursts — intergalactic medium — ISM: abundances — ISM: kinematics and dynamics

Online material: color figure

1. INTRODUCTION

Various surveys designed to detect emission at optical, near-infrared, and submillimeter wavelengths have yielded large samples of galaxies at redshift $z > 2$ (e.g., Steidel et al. 1999; Blain et al. 2002), but whether these galaxies are representative of the galaxy population at high redshifts and how they are related to the local population are not clear. Damped Lyα absorption (DLA) systems probe high-redshift gaseous clouds of neutral hydrogen column density N(H I) consistent with what is observed in the disks of nearby luminous galaxies (e.g., Wolfe et al. 2005). They are selected uniformly with N(H I) $\geq 2 \times 10^{20}$ cm^{-2} and represent a unique sample of distant galaxies with known interstellar medium (ISM) properties from absorption-line studies (e.g., Pettini et al. 1999; Prochaska et al. 2003). Identifying the stellar counterpart of the DLAs has, however, been challenging because of the glare of background quasars (Colbert & Malkan 2002; Le Brun et al. 1997; Rao et al. 2003; Chen & Lanzetta 2003).

Long-duration gamma-ray bursts (GRBs) are believed to originate in the death of massive stars (e.g., Woosley 1993; Paczyński 1998; Bloom et al. 2002; Stanek et al. 2003). Some bursts are followed by optical afterglows (e.g., Akerlof et al. 1999) that can briefly exceed the absolute brightness of any known quasar by orders of magnitude and serve as bright background sources for probing intervening gas along the line of sight. Because of their transient nature, however, optical afterglows do not interfere with follow-up studies of absorbing galaxies close to the sight lines. Early-time high-resolution spectroscopy of GRB afterglows, together with deep late-time imaging of galaxies along the sight lines, offers a novel means to uncover a sample of high-redshift galaxies based on their absorption properties. In the context of hierarchical structure formation, GRB progenitors can form before massive black holes and therefore may be used to probe the early universe, well into the age of reionization.

Prompt localization of GRB afterglows is critical in order to take advantage of their brief but extreme brightness for acquiring echelle spectroscopy. It has been difficult in the past to carry out rapid spectroscopy for the optical transient (OT) because of the time-consuming processes of localizing the bursts. Despite an extensive effort, only a small number of GRBs have been spectroscopically identified at $z > 2$ with low-to-moderate resolution spectra available,[6] and only two have been identified with echelle data available (Fiore et al. 2005). Together these data show that all GRB host galaxies have abundant neutral gas and that some have the largest N(H I) among all DLA systems (Jensen et al. 2001; Møller et al. 2002; Castro et al. 2003; Jakobsson et al. 2004; Vreeswijk et al. 2004).

The current-generation gamma-ray satellite, *Swift*, is de-

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[6] See http://www.mpe.mpg.de/~jcg/GRBgen.html for a complete list.

signed to provide nearly instant localization of new GRBs. Over the past 2 years, our group has been pursuing well-localized GRB afterglows with moderate-to-high resolution spectroscopy (e.g., Prochaska et al. 2004; Bloom et al. 2005). The primary goal of our project is to collect a statistically significant sample of galaxies along the sight lines toward high-redshift afterglows. This galaxy sample includes both GRB host galaxies and those foreground DLA galaxies that are close to the sight lines. While intervening DLA systems arise preferentially in the outskirts of distant galaxies (because of a gas cross section selection effect), the GRB host sample offers a unique opportunity to study ISM physics more immediate to vigorous star-forming regions in high-redshift galaxies (which have relatively small cross sections).

Here we present the first echelle spectrum of a *Swift* GRB, obtained 4 hr after the burst. The spectrum, which spans a wavelength range from 3300 through 9400 Å, exhibits abundant absorption features superposed on a simple power-law shaped continuum. We identify the GRB at $z_{\rm GRB} = 3.969$ based on a strong damped absorption trough centered at 6040 Å and a suite of associated metal absorption features. In addition, we identify an intervening DLA system at $z_{\rm DLA} = 3.564$ and a number of strong Mg II absorbers along the sight line. We demonstrate that rapid echelle spectroscopy is plausible for well-localized afterglows and that the observations provide new insight into the nature of GRB host environments, as well as the physical properties of the intergalactic medium (IGM) along the sight lines.

2. OBSERVATIONS AND DATA REDUCTION

We observed the OT of GRB 050730 that was first reported by Holland et al. (2005) and later confirmed by Sota et al. (2005) at R.A. $= 14^{\rm h}8^{\rm m}17\overset{\rm s}{.}14$ and decl. $= -3°46'17\overset{''}{.}8$ (J2000.0), using the MIKE echelle spectrograph (Bernstein et al. 2003) on the 6.5 m Magellan Clay telescope at Las Campanas Observatory. The spectrograph contains a blue camera and a red camera, allowing a full wavelength coverage from near-ultraviolet 3300 Å through near-infrared 9400 Å. The observations were carried out in a sequence of three exposures of duration 1800 s each, starting at UT 00:00 on 2005 July 31 (4 hr after the initial burst) when the OT had $R \approx 17.7$ (Holman et al. 2005). The mean seeing condition over the period of integration was $0\overset{''}{.}7$. We used a $0\overset{''}{.}7$ slit and 2×2 binning during readout, yielding a spectral resolution of FWHM $\approx$ 10 km s^{-1} at wavelength $\lambda = 4500$ Å and $\approx$12 km s^{-1} at $\lambda = 8000$ Å. The data were processed and reduced using the MIKE data reduction software developed by S. Burles, J. X. Prochaska, and R. Bernstein.[7] Wavelengths were calibrated to a ThAr frame obtained immediately after each exposure and subsequently corrected to vacuum and heliocentric wavelengths. Flux calibration was performed using a sensitivity function derived from observations of the flux standard NGC 7293.

The final stacked spectrum of the afterglow is presented in Figure 1. The signal-to-noise ratio (S/N) of the echelle data is S/N $=$ 12 at 4800 Å and S/N $=$ 13 at 8000 Å per resolution element. We have performed a χ^2 fitting routine over the spectral region between 7000 and 9000 Å, corresponding to a wavelength range between 1400 and 1800 Å in the rest frame of the host, and obtained a best-fit power-law model $f_\nu(\lambda) \propto \lambda^\alpha$ with $\alpha = 1.88 \pm 0.01$, which is presented as the red dotted curve in Figure 1. The best-fit power-law index is significantly steeper than what has been measured for the OT of GRB 020813 ($\alpha = 1$) at rest-frame optical wavelengths (Barth et al. 2003).

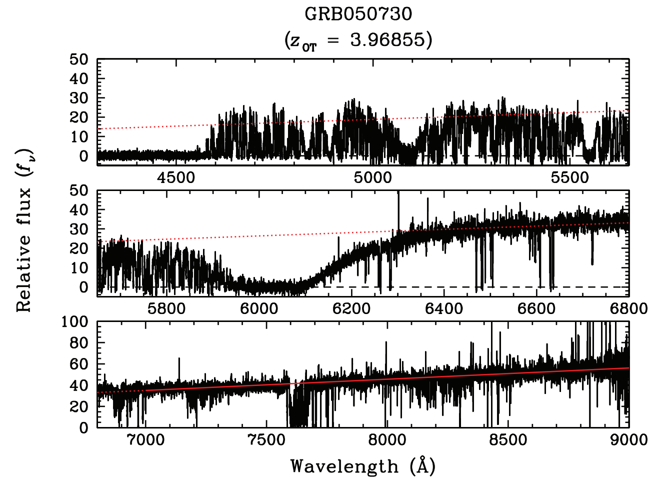

FIG. 1.—Stacked echelle spectrum of the OT of GRB 050730. The S/N of the echelle data is S/N $=$ 12 at 4800 Å and S/N $=$ 13 at 8000 Å per resolution element. Blueward of the Lyα absorption trough at 6040 Å from the GRB host environment is a forest of foreground Lyα absorbers, including a DLA system at 5550 Å ($z_{\rm DLA} = 3.564$). The Lyβ absorption feature of the GRB host is apparent at 5090 Å. The absence of flux at wavelengths below 4530 Å indicates that few or no high-energy photons beyond the Lyman limit transition escape the host of the GRB. The continuum at $\lambda = 7000$–9000 Å is best described by a power-law model $f_\nu(\lambda) \propto \lambda^{1.88}$, as shown by the red dotted curve. Note that the power-law fit from 7000 to 9000 Å somewhat underpredicts the apparent continuum flux from 4600 to 5000 Å (*red dotted curve*).

3. ANALYSIS

The echelle spectrum of the OT of GRB 050730 exhibits a large number of absorption features due to the H I Lyα transition and various heavy ions in the ISM of the GRB host, as well as in intervening gaseous clouds at $z < z_{\rm GRB}$. Most notable is the strong damping trough centered at roughly 6040 Å, blueward of which we observe a forest of absorption features that are not present on the red side of the damped absorption profile. We identify the damped absorber as the DLA originating in the host galaxy of the GRB at $z_{\rm GRB} = 3.969$ and the forest lines as the Lyα forest at $z < z_{\rm GRB}$. In addition, we also identify an intervening DLA at $z_{\rm DLA} = 3.564$ and a number of strong metal-line absorbers. Here we summarize the physical properties of these strong absorbers.

3.1. *The GRB Host Environment at* $z_{\rm GRB} = 3.969$

The redshift measured for the GRB host using the DLA feature is confirmed by associated metal-line transitions. We measure a more precise redshift of the GRB at $z_{\rm GRB} = 3.96855 \pm 0.00005$ using narrower metal absorption lines. At this redshift, we measure the N(H I) value of the GRB host by fitting Voigt profiles to the observed Lyα and Lyβ transitions simultaneously using the VPFIT software package.[8] We obtain log N(H I) $= 22.15 \pm 0.05$ for the host, with the error estimated from varying the continuum level of the absorption line profiles. This is the highest N(H I) observed in DLA systems, including those arising in GRB hosts (cf. Vreeswijk et al. 2004).

In addition to absorption features due to neutral hydrogen,

[7] See http://web.mit.edu/~burles/www/MIKE/mike_cookbook.html.

[8] See http://www.ast.cam.ac.uk/~rfc/vpfit.html.

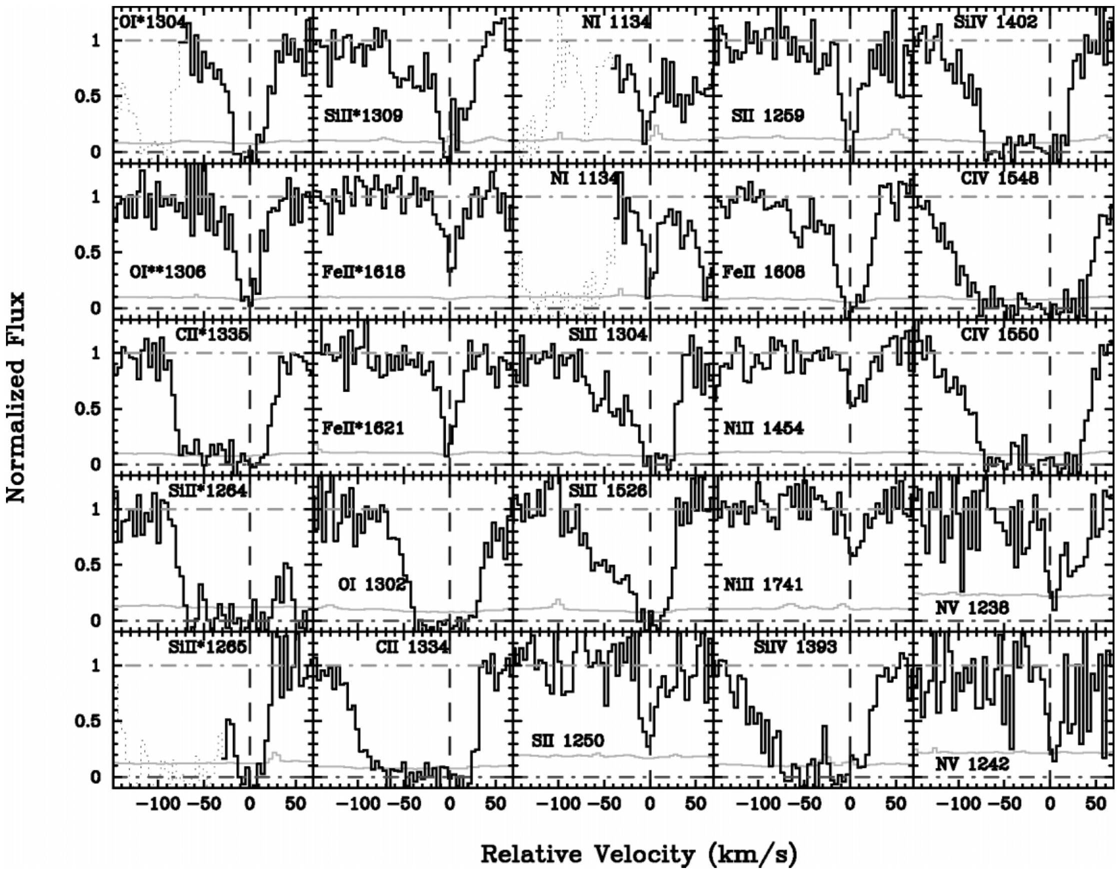

FIG. 2.—Absorption profiles of different ionic transitions found at the redshift of the GRB host. The 1 σ error spectrum is presented as the thin curve above the dash-dotted line in each panel. The zero relative velocity corresponds to redshift $z = 3.96855$. [*See the electronic edition of the Journal for a color version of this figure.*]

the spectrum also exhibits a suite of metal absorption lines at the GRB host redshift (Fig. 2), from neutral species such as O I, to low-ionization transitions such as C II, Si II, S II, Ni II, and Fe II, and to high-ionization transitions such as C IV, Si IV, and N V. We also identify strong fine-structure lines such as O I*, O I**, Si II*, C II*, and Fe II*. With the exception of C II* (Wolfe et al. 2003), none of these transitions has been detected in intervening DLA systems. In particular, Fe II* absorption features are only observed locally in η Carinae (Gull et al. 2005). These saturated fine-structure transitions indicate an extreme ISM environment with high gas density that is rarely observed in intervening DLA systems. Furthermore, the profiles of well-resolved lines (e.g., S II λ1250) show that >90% of the neutral gas is confined to a velocity width of 20 km s^{-1}, which is considerably smaller than the median value of intervening DLA systems and implies a quiescent environment. But the profiles of saturated lines do exhibit absorption extending to $\approx$80 km s^{-1} (e.g., Si II λ1526). Finally, the asymmetry of these line profiles is suggestive of an organized velocity field, e.g., rotation or outflow.

We measure the column density of each transition using both the apparent optical depth method (Savage & Sembach 1991) and the VPFIT software package. Comparing column density ratios between different transitions allows us to constrain the physical properties of the ISM in the GRB host. The principal results are as follows. (1) We measure [S/H] $= -2.0 \pm 0.1$. Because S is nonrefractory, its gas-phase abundance gives a direct measurement of the gas metallicity. (2) We find [S/Fe] $= +0.3$, consistent with the gas-phase [α/Fe] measurements of low-metallicity DLA systems. Even if we adopt an intrinsic solar abundance pattern, the dust-to-gas ratio in the host ISM is very low (cf. Savaglio et al. 2003). (3) We measure [N/S] $= -1.0 \pm 0.2$, again consistent with low-metallicity DLA systems (Prochaska et al. 2002). (4) We detect no molecular lines in the Lyα forest, suggesting a warm gas phase. (5) Based on the observed ratio of N(Fe II*)/N(Fe II), we infer a number density $n_H > 10^3$ cm^{-3} for a temperature $T < 30{,}000$ K. This constrains the size of the host DLA cloud to be $l_{DLA} < 4.6$ pc.

In summary, aside from the large gas density n_H inferred from saturated fine-structure lines, the ISM of the GRB host has very similar characteristics to known DLA systems at $z \sim 4$.

3.2. *Intervening Absorbers*

We have identified a number of strong absorbers along the sight line toward GRB 050730. We briefly summarize each system here.

DLA system at $z_{DLA} = 3.56439$.—We identify Lyα and Lyβ transition for this absorber and measure log N(H I) $= 20.3 \pm 0.1$. In addition, we also find associated metal-line absorbers due to Si II, Al II, Fe II, Si IV, and C IV. The weak line strengths of these metal absorption lines suggest a low metallicity in the neutral gas, [Si/H] < -1.3.

Lyman limit system at $z_{LLS} = 3.02209$.—We measure N(H I) using the Lyα feature and find log N(H I) $= 19.9 \pm 0.1$ for this Lyman limit system. In addition, we identify Si II, Al II, and Fe II, but we do not detect C IV absorption at the absorber redshift. Including no ionization correction, we find $[Si/H] = -1.5 \pm 0.2$.

Mg II *system at* $z_{\rm Mg\,II} = 2.25313$.—We identify a saturated Mg II doublet at this redshift. In addition, we find strong Mg I λ2852 and Fe II absorption features for this absorber.

Double Mg II *systems at* $z_{\rm Mg\,II} = 1.7731$.—We identify a pair of Mg II absorbers at $\Delta v = 57$ km s^{-1} apart, for which we also find Mg I λ2852 and the Fe II absorption series.

4. DISCUSSION AND CONCLUSIONS

GRB afterglows clearly provide a novel alternative to quasars for probing the ISM and IGM in the young universe. In the case of GRB 050730, the afterglow reached an initial brightness of $R = 15.5$ (Klotz et al. 2005) and faded to $R = 17.5$ 4 hr later when the echelle spectroscopy was commenced. At $z = 3.969$, $R = 15.5$ corresponds to an absolute magnitude $M_{1450} = -29.3 + 5 \log h$ at rest frame 1450 Å.[9] This intrinsic luminosity within a minute after the burst is comparable to the most luminous quasar known (cf. HS 1700+6416 at $z = 2.73$; Schneider et al. 2003). Even at $R = 17.5$, the corresponding intrinsic luminosity easily competes with the brightest quasars known at this redshift (see, e.g., Fan et al. 2001). While absorption-line systems uncovered toward the sight lines of optically selected quasars are likely to miss dusty absorbers, the extreme brightness of early GRB afterglows offers an unbiased view of the IGM at all epochs. In addition, the simple power-law shaped continuum of a GRB afterglow allows a more precise and accurate measurement of IGM opacity.

The sight line toward GRB 050730 is particularly interesting, with a strong DLA feature arising in the GRB host galaxy and an intervening DLA system at lower redshift. GRB-host DLA systems ($z_{\rm DLA} = z_{\rm GRB}$), which are presumably selected by vigorous star formation and therefore probe deep into the center regions of distant galaxies, present a nice contrast to the intervening DLA systems ($z_{\rm DLA} < z_{\rm GRB}$), which arise preferentially at large galactocentric radii due to the cross section of the outskirts being larger than that of the inner regions. Our study shows that aside from having a much higher neutral gas density, the GRB-host DLA has characteristics very similar to those of known $z \sim 4$ DLA systems, such as low dust content, low metallicity, and α-element–enhanced chemical composition.

We have also shown that this sight line runs through a number of strong intervening absorbers, including a Lyman limit system and two strong Mg II absorbers. Detailed analyses of various ionic transitions associated with these absorbers allow us to study physical properties of the ISM and IGM over a wide redshift range from $z = 1.7$ through $z = 3.9$. Follow-up deep imaging and low-resolution spectroscopy of faint galaxies along the line of sight will allow a direct comparison between the physical properties of the cold ISM (such as metallicity, kinematics, and dust content as derived from absorption-line studies) and stellar properties (such as luminosity, morphology, and star formation rate as extracted from absorbing-galaxy analyses). A large sample of GRB-host DLA systems offers a unique opportunity to dissect the ISM properties that are directly connected to GRBs, while a statistical sample of intervening DLA systems identified toward GRB sight lines will provide important insights toward understanding the nature of high-redshift DLA systems and offer a simple test to discriminate between different galaxy formation scenarios (e.g., Haehnelt et al. 2000).

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[9] Adopting a Λ cosmology, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$, with a dimensionless Hubble constant $h = H_0/(100$ km s^{-1} Mpc$^{-1})$.

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